Classical fields in heavy-ion collisions

Vladimir Skokov

Brain workshop

Outline

- Raju Venugopalan this morning: Glasma and thermalization

Outline

- Raju Venugopalan this morning: Glasma and thermalization
- Electromagnetic fields acting on in- and out-of-equilibrium plasma

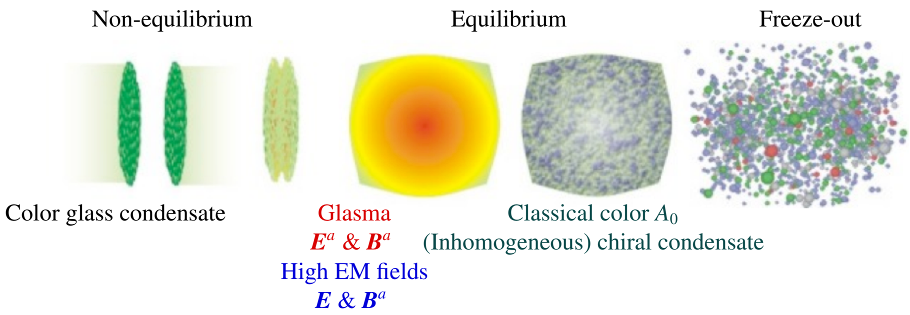
Outline

- Raju Venugopalan this morning: Glasma and thermalization
- Electromagnetic fields acting on in- and out-of-equilibrium plasma
- Color fields in-equilibrium: non-trivial holonomy A_0

Outline

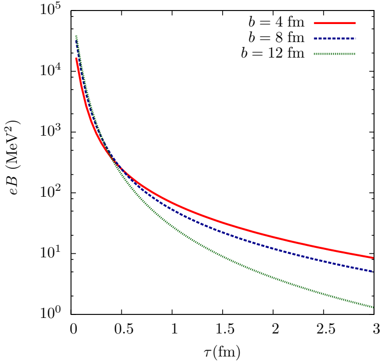
- Raju Venugopalan this morning: Glasma and thermalization
- Electromagnetic fields acting on in- and out-of-equilibrium plasma
- Color fields in-equilibrium: non-trivial holonomy A_0
- Chiral condensate and manifestation of its dynamics: chiral crossover, chiral critical point, quarkyonic phase

Classical field in heavy-ion collisions

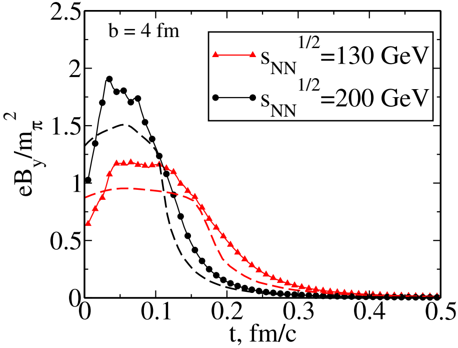


Almost on every stage of heavy-ion collisions, classical fields play significant role.

HICs create not only strong color
but also extremely strong (electro)-magnetic fields.
Strong ≡ of the hadronic scales, $eB \sim m_\pi^2$.



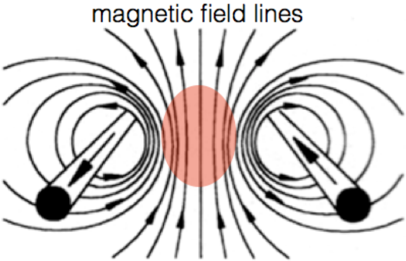
D. Kharzeev, L. McLerran and H. Warringa
Nucl.Phys. A803 (2008) 227-253



V. S., Y. Illarionov and V. Toneev
arXiv:0907.1396

Origin of (electro)-magnetic field in HIC

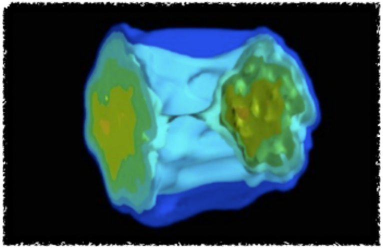
In the first approximation, colliding nuclei are two positive charges moving with ultra relativistic velocities in opposite directions.



Two currents in opposite direction. Magnetic fields of the two sources add up, while electric fields nearly cancel each other. Out-of-plane direction of magnetic field:

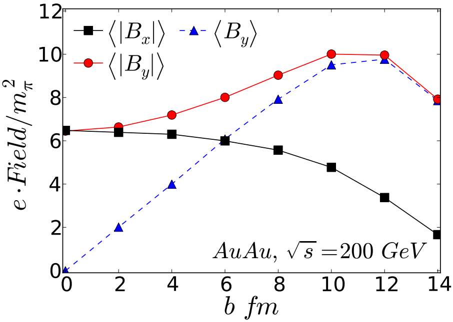
$$\langle eB_y \rangle \sim m_\pi^2, \langle eB_x \rangle \sim \langle eB_z \rangle \sim 0$$

$$\langle eE_x \rangle \sim \langle eE_y \rangle \sim \langle eE_z \rangle \sim 0$$



Charge distribution in nuclei is not uniform. Lumpy distribution of electric charge in colliding nuclei results in nonzero randomly oriented magnetic field even in central collisions.

A. Bzdak and V.S.
Phys.Lett. B710 (2012) 171



- Fluctuations of participant and reaction planes
  (J. Bloczynski et al, Phys.Lett. B718 (2013) 1529)
- Non-zero electric field can induce separation of charges;
  $\boldsymbol{j} = \sigma \boldsymbol{E}$
  measurements of electric conductivity (talk by Y. Hirono)
- Lifetime of (electro)-magnetic field?!

LIFETIME OF MAGNETIC FIELD

External magnetic field might live longer because of conductivity effects:

$$\boldsymbol{j} = \sigma_{\rm Ohm} \cdot \boldsymbol{E} + \sigma_\chi \cdot \boldsymbol{B}$$

where $\sigma_{\rm Ohm}$ is electric conductivity and σ_χ is chiral-magnetic conductivity (D. Kharzeev et al).

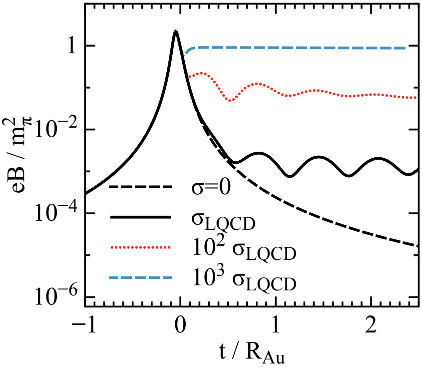
Electric conductivity:

quenched lattice QCD calculations $\sigma^{\rm LQCD}_{\rm Ohm} = (5.8 \pm 2.9)\frac{T}{T_c}$MeV.

Chiral magnetic conductivity:

$\sigma_\chi = \left(\frac{e^2}{2\pi^2} N_c \sum_f q_f^2\right)\mu_5$, let $\mu_5 \sim 1$ GeV, then $\sigma_\chi \sim 15$ MeV.

Lifetime of magnetic field



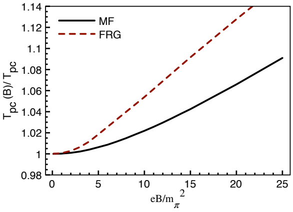
S. Lin, L. McLerran and V.S.

- Even for $\sigma_{\text{Ohm}} = 10^2 \sigma_{\text{Ohm}}^{\text{LQCD}}$ magnetic field falls quite fast.
- $\sigma_{\text{Ohm}} \sim \sigma_{\text{Ohm}}^{\text{LQCD}}$ is an optimistic estimate, since in early stage there are no charge carriers
- Magnetic field acts on very early (non-equilibrium) nuclear matter

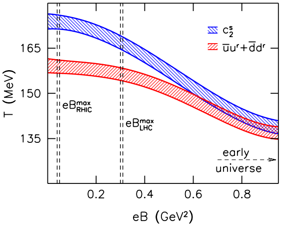
Modification of QCD phase diagram in high magnetic field.

Probably (unless system is in local equilibrium at times less then 0.1 fm/c), not relevant for HIC phenomenology owing to short lifetime of magnetic field.

Nonetheless, as we learned from talk by Y. Hidaka, QCD calculations with magnetic field showed that existing low-energy effective models does not capture essential chiral and deconfinement properties of QCD.



V.S. Phys.Rev. D85 (2012) 034026



G. S. Bali et al JHEP02 (2012) 044

FRG: functional renormalization group will be discussed in talk by Y. Tanizaki

- **Chiral Magenetic Effect and Chiral Magnetic Wave**: $j \sim \sigma_\chi B$.
- **Photon production in strong magnetic field**

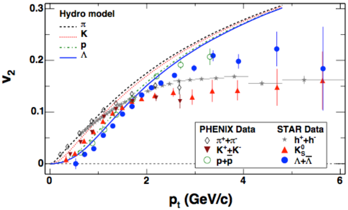
  Conformal anomaly: G. Bazar, D. Kharzeev and V.S. Phys.Rev.Lett. 109 (2012) 202303

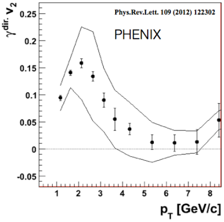
  Chiral anomaly: K. Fukushima and K. Mameda Phys.Rev. D86 (2012) 071501

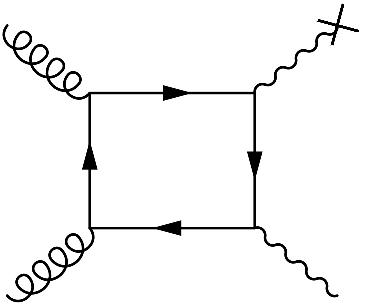
  Ho-Ung Yee, arXiv:1303.3571

Photon azimuthal anisotropy (quantified by v_2) is approximately the same as for charge particles. In contradiction to expectations: photon production $\sim T^4$, however, momentum azimuthal anisotropy is small.

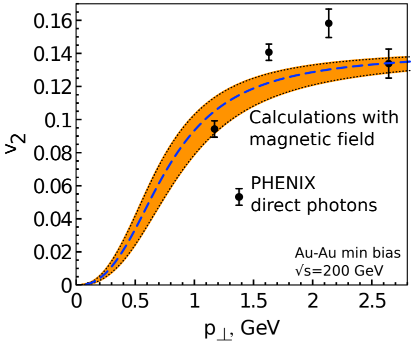
Hydrodynamic calculations underestimate photon v_2 by factor of 5.







If magnetic field of hadronic scales $eB \sim m_\pi^2$, two gluon produce one photon with rate similar to quark-antiquark annihilation and Compton scattering.



Usually photon production from two gluons is suppressed by α_{EM} compared to quark-antiquark annihilation or Compton scattering

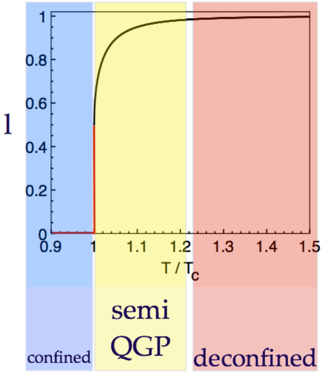
Experimental data was underpredicted by a factor of **5** in hydro calculations.

Photon production details

- Resummed contribution from gluons in color singlet state.
- In vacuum, dilaton is an effective description of Yang-Mills theory. Assumption: single scalar meson saturates conformal anomaly. Dilatation current acting color singlet states
  $\langle 0|D^\mu|\sigma\rangle = iq^\mu f_\sigma;\ \ \langle 0|\partial_\mu D^\mu|\sigma\rangle = m_\sigma^2 f_\sigma$
  From decay of lowest glueball state to two photons decay to two photons coupling $g_{\sigma\gamma\gamma}$ of following effective Lagrangian is obtained
  $\mathcal{L}_{\sigma\gamma\gamma} = g_{\sigma\gamma\gamma}\ \sigma\ F_{\mu\nu}F^{\mu\nu}$ with
  $\sigma \sim \theta^\mu_\mu = \partial^\mu D_\mu = \theta^\mu_\mu = \frac{\beta(g)}{2g} G^{\mu\nu a}G_{\mu\nu a} + \sum_q m_q(1+\gamma_m(g))\bar{q}q,$
- Photon production rate
  $q_0 \frac{d^3\Gamma}{dq^3} \propto \left[(B_y^2 - B_x^2)q_x^2 + Bx^2 q_\perp^2\right]\rho_\theta(q_0),$
  where $\rho_\theta(q_0)$ is spectral function for trace of energy momentum tensor, in hydrodynamical limit $\rho_\theta(q_0) \approx \frac{9}{\pi} q_0 \zeta$

Non-trivial holonomy A_0 at finite T

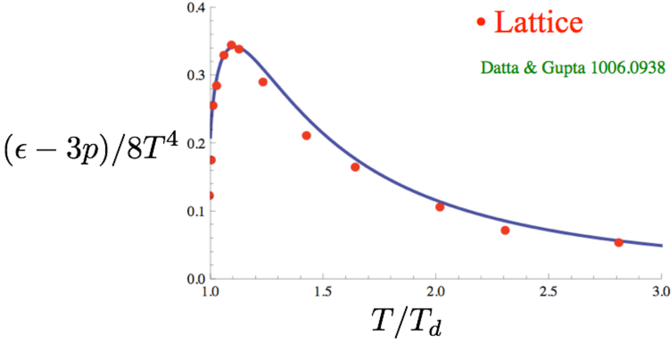
- In equilibrium, color background field A_0 is expected
- Characterized by Polyakov loop $L = Tr\,\mathcal{P}\exp\left(ig\int_0^{1/T} A_0 d\tau\right)$, which also play a role of order parameter for deconfinement in Yang Mills theory



R. Pisarski

- Effective theory to study properties of YM sector
- High T: effective potential obtained perturbatively
  $V^{\mathrm{pert}} = \frac{2\pi^2}{3}T^4\left(-\frac{4}{15}(N_c^2-1)+\sum_{ij=1}^{N_c} q_{ij}^2(1-q_{ij})^2\right)$,
  $q_{ij} = |q_i - q_j|$
  Anzatz $A_0^{ij} = \frac{2\pi T}{g} q_i \delta^{ij}$, $\sum_i q_i = 0$
  (Gross-Pisarski-Yaffe/Weiss potential)
- Non-trivial solution for q_i demands non-perturbative potential which is assumed to be
  $V^{\mathrm{non-pert}} = T^2 T_d^2 \left[C_1 \sum_{ij=1}^{N_c} q_{ij}^2(1-q_{ij})^2\right.$
  $\left. + C_2 \sum_{ij=1}^{N_c} q_{ij}(1-q_{ij}) + C_3\right]$
  Further discussion in talk by K. Kashiwa

Comparison to lattice



A. Dumitru et al Phys.Rev. D86 (2012) 105017

Good description of YM thermodynamics, interface tension for SU(2) and SU(3).

Large N_c limit

- Potential in explicit form

$$V/(N_c^2-1) \equiv \widetilde{V}_{\text{eff}}(q) \;=\; -\,d_1(T)\,\widetilde{V}_1(q) \;+\; d_2(T)\,\widetilde{V}_2(q)\;,$$

$$\widetilde{V}_n(q) = 1/(N_c^2-1)\sum_{i,j=1}^{N_c} |q_i-q_j|^n(1-|q_i-q_j|)^n$$

- It is useful to introduce eigenvalue density
$\rho(q) = \frac{1}{Nc}\sum_i \delta(q-q_i) \to \int_0^1 dx\delta(q-q(x)) = dx/dq$
Then

$$1/N_c\sum_i f(q_i) \to \int_0^1 dx f(q_x) = \int dq\frac{dx}{dq}f(q) = \int dq\rho(q)f(q)$$

- Terms in the potential

$$V_n(q) = \int dq\int dq'\,\rho(q)\,\rho(q')|q-q'|^n(1-|q-q'|)^n\;.$$

non-local field theory

Solution in large N_c limit

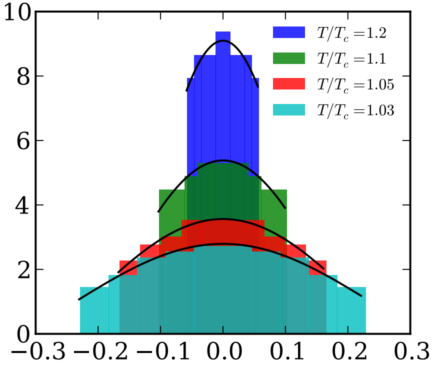
- Solution for eigenvalue density ($d = 12 d_2/d_1$)

$$\rho(q) = 1 + b\cos(d\,q) \quad , \quad q : -q_0 \to q_0$$

- q_0 and b are given by

$$\cot(d\,q_0) = \frac{d}{3}\left(\frac{1}{2} - q_0\right) - \frac{1}{d\,(1/2 - q_0)} \,,$$

$$b^2 = \frac{d^4}{9}\left(\frac{1}{2} - q_0\right)^4 + \frac{d^2}{3}\left(\frac{1}{2} - q_0\right)^2 + 1$$



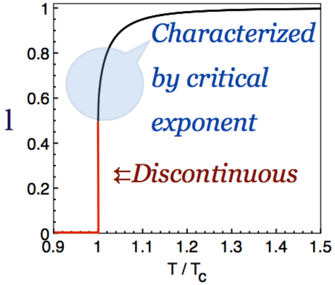
R. Pisarski and V.S.
Phys.Rev. D86 (2012) 081701

Gross-Witten-Wadia phase transition

What is order of deconfinement phase transition in large N_c limit?

Effective matrix model: critical first order phase transition (PT): aspects of both first order and second order PTs.

- Discontinuity as in first order PT. Approaching T_d+ Polyakov loop jumps from 0.5 to 0.
- Divergence of order parameter susceptibility as in second order PT.



Critical exponents obtained analytically:

$$l \sim (T/T_d - 1)^{\beta}, \quad \beta = 2/5$$

$$c_V \sim (T/T_d - 1)^{-\alpha}, \quad \alpha = 3/5$$

$$l - 1/2 \sim h^{1/\delta}, \quad \delta = 5/2$$

Griffith's scaling relation $2 - \alpha = \beta(1 + \delta)$ is satisfied.

GWW PT was also obtained in $SU(\infty)$ on femtosphere. This suggests that in infinite volume, the Gross-Witten-Wadia transition may be an infrared stable fixed point of a $SU(\infty)$ gauge theory.

- A_0 modifies not only thermodynamics
- Scattering processes are also modified compared to perturbative/HTL results, e.g.
  - shear viscosity $\eta \sim l^2$
  - heavy-quark energy loss $dE/dx \sim l$
  - hard photon production $q_0 d\Gamma/dq^3 \sim l$ (another step to solve photon v_2 puzzle)
  - dilepton production $q_0 d\Gamma/dq^3 \sim (1 - l)$
  - work in progress Y. Hidaka, S. Lin, R. Pisarski and V. S.

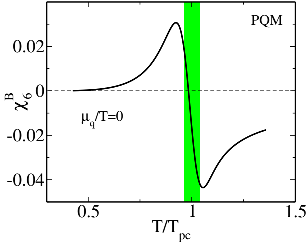
Outlook

I had no time to talk about:

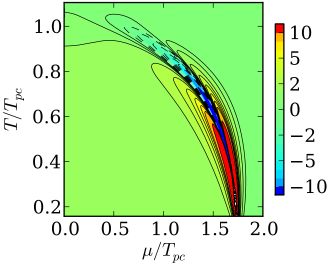
- Quark production in Glasma: F. Gelis, K. Kajantie and T. Lappi
  perturbative results not reproduced at large $k_\perp$

  Quark production in Glasma in presence of strong (electro)magnetic field
  work in progress R. Venugopalan and V.S.

- Chiral condensate and its manifestation in HIC (talk by K. Morita):
  - signals of criticality on crossover phase transition line



  - signals critical point



Kurtosis of baryon number fluctuations

  - signals of quarkyonic phase
  - background contribution (baryon number conservation, volume fluctuations and etc)

Conclusions

- (Electro)magnetic field in HIC is of hadronic scales. Short lifetime. It gives significant contribution to photon azimuthal anisotropy at RHIC energies. Motivated to study QCD at finite magnetic field.
- Non-trivial classical A_0 field: effective description of Yang-Mills thermodynamics. Modification of scattering processes.In large N_c limit, deconfinement phase transition in $SU(\infty)$ theory is of Gross-Witten-Wadia type?! This is suggested both by an effective model and $SU(\infty)$ on femtosphere.